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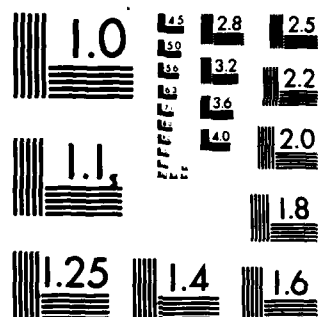
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# NOTE

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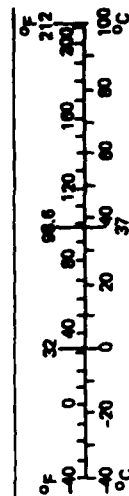
# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
<b>AREA</b>				
in <sup>2</sup>	square inches	6.5	square centimeters	cm <sup>2</sup>
ft <sup>2</sup>	square feet	0.09	square meters	m <sup>2</sup>
yd <sup>2</sup>	square yards	0.8	square meters	m <sup>2</sup>
mi <sup>2</sup>	square miles	2.6	square kilometers	km <sup>2</sup>
	acres	0.4	hectares	ha
<b>MASS (weight)</b>				
oz	ounces	28	grams	g
lb	pounds (16 oz)	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
<b>VOLUME</b>				
tsp	teaspoons	5	milliliters	ml
Tabsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft <sup>3</sup>	cubic feet	0.03	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.76	cubic meters	m <sup>3</sup>
<b>TEMPERATURE (exact)</b>				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

## Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
<b>LENGTH</b>				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
<b>AREA</b>				
cm <sup>2</sup>	square centimeters	0.16	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	1.2	square yards	yd <sup>2</sup>
km <sup>2</sup>	square kilometers	0.4	square miles	mi <sup>2</sup>
ha	hectares (10,000 m <sup>2</sup> )	2.5	acres	
<b>MASS (weight)</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
<b>VOLUME</b>				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m <sup>3</sup>	cubic meters	36	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.3	cubic yards	yd <sup>3</sup>
<b>TEMPERATURE (exact)</b>				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



\* 1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 288, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10:288.

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A new approach to burning coal in industrial-size boilers without being constrained by the sulfur content of the fuel was investigated. Coal combustion with the injection of a lime sulfur sorbent was evaluated using an equilibrium combustion computer program. Subsequent experimental work with a flame tube apparatus demonstrated that lime does react effectively with hydrogen sulfide in a low temperature, fuel-rich flame. Applications for this approach include both existing boilers designated for other fuels and new boilers designed for coal firing.

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## INTRODUCTION

### Background

The demand for coal burning depends on the balance between the supply of petroleum fuels and economic, environmental, and political considerations. The technology for expedient coal burning has been available for centuries. However, the technology for environmentally acceptable coal use is only in its infancy. As the nation's and the world's petroleum reserves decrease, the need for a viable alternative fuel will develop. Coal constitutes the most abundant fossil fuel resource in this country. The estimated life of recoverable reserves varies from about 50 years to several centuries, depending upon estimates for both the extraction growth rate and the quantity of the reserves. Coal could, therefore, be little more than an interim measure until renewable energy resources are operational, or it could literally be the mainstay of future energy conversion.

Most Navy combustion hardware uses liquid or gaseous fuels which are in short supply. Navy boilers are in the industrial-size range, with the largest individual units rated at about 250 MBtu/hr. However, combinations of boilers in steam plants sometimes exceed this steam generating capacity.

One plan to increase the amount of coal burned would be either to make or to buy coal-based synthetic liquid and/or gaseous fuels and distribute them to existing boilers. This option has been analyzed in great detail and was found to be too costly for consideration now. In addition, a viable synthetic fuel industry does not exist. This limits realistic synthetic fuel options to the on-base manufacture of either low-Btu gas, medium-Btu gas, or methyl fuel (Ref 1, 2).

Another possible solution is the purchase or manufacture of coal mixture fuels. The preparation of such fuels involves mixing finely ground coal with either oil or water or both. Surfactants are often added to maintain the stability of the mixture and to alter its physical properties. For example, a simple mixture of coal powder and residual fuel oil is very viscous. The addition of surfactants and up to 30% water decreases viscosity markedly.

Coal mixture fuels increase the use of coal and decrease the use of oil. In general, they represent only an interim solution, and the extent of their impact has yet to be determined. For example, it is unlikely that a new facility would be designed to burn them as a primary fuel. Their use in a boiler designed for liquid fuels requires modifications for air pollution control, ash handling, and internal soot and ash removal. In short, the demand for coal mixture fuels will peak while existing boilers burn them and will dwindle as these boilers are eventually replaced with those designed for either synthetic fuels or direct coal firing. It should be noted that the Navy's economic design life



for a boiler is 25 years. On the other hand, well-maintained older boilers exceed the design life without difficulty. Therefore, there is still a need for new approaches that extend the useful life of existing boilers.

### Objective

The objective of this project was to develop a means whereby coal could be burned, without being environmentally constrained by its sulfur content, in industrial-size oil- and gas-fired Navy boilers. Actually, there were two objectives. The first was to establish the technical viability of a new concept, and the second was to demonstrate an economic need for the continued development and implementation of the actual hardware. Only the first was considered here.

### Theory

It was proposed to control sulfur emissions by burning superfine or ultrafine grind coal dust (325 mesh or finer) without adequate oxygen in the presence of lime or limestone dust. Combustion would take place in two stages. The first stage would provide fuel rich or starved air combustion conditions. Insufficient air for complete combustion would also control combustion temperatures. The first stage burner would serve as a reactor by providing enough residence time for the sulfur-removing sorbent to react (Ref 3). This concept departs from past work and depends in part on the technology developed for coal slurry burning and in part on fluidized bed gasification and combustion technology.

Prior experimental efforts have indicated that the direct injection of limestone into a stoker-fed boiler presents a number of problems. The degree of  $\text{SO}_2$  absorption is low because retention time is low and there is minimal  $\text{SO}_2$  penetration beyond the surface layer. Unreacted lime in the gas stream reduces the efficiency of electro-static precipitators.

When a hydrocarbon fuel is burned with adequate combustion air, the ideal combustion products are  $\text{CO}_2$ ,  $\text{H}_2\text{O}$  and  $\text{N}_2$ . If sulfur is present in the fuel, it is oxidized to  $\text{SO}_2$ . If insufficient air is present (fuel rich), the reaction cannot go to completion, and the reaction can be forced to produce  $\text{CO}$ ,  $\text{H}_2$ ,  $\text{H}_2\text{S}$ , and  $\text{N}_2$ . The latter is the primary reaction in an air-blown coal gasifier. The key differences are the production of  $\text{H}_2\text{S}$  instead of  $\text{SO}_2$ , and the dissociation of the reacting species in the presence of the sorbent. Since  $\text{H}_2\text{S}$  is much more reactive than  $\text{SO}_2$ , it should be more readily removed by a sorbent such as lime ( $\text{CaO}$ ). In the past, it was shown that either lime or limestone injection was not particularly effective for the removal of  $\text{SO}_2$ . On the other hand, the reaction of  $\text{CaO}$  with  $\text{SO}_2$  in a fluidized bed to produce gypsum ( $\text{CaSO}_4$ ) is very effective. Gypsum is a particularly good waste product; it is a very stable, dry solid that can be either recycled or discarded in a landfill.

The reaction of  $\text{H}_2\text{S}$  with  $\text{CaO}$  would produce calcium sulfide ( $\text{CaS}$ ). Since  $\text{CaS}$  can decompose, it would be preferable to oxidize it to form gypsum in the second stage of a two-stage combustion process. This

would be accomplished by air injection after the first stage. Combustion temperature control is very important because the desired reactions are temperature sensitive, and neither the ash nor the sorbent should be allowed to soften. Softening would lead to fouling of the boiler tubes and walls. In order to control combustion temperatures, particularly for the second stage, it would be necessary to lower temperatures by heat transfer away from the flame.

The terms lime and limestone are often used loosely. Strictly speaking, limestone is calcium carbonate ( $\text{CaCO}_3$ ), and lime is calcium oxide ( $\text{CaO}$ ). Dolomite is a mixture of calcium and magnesium carbonates ( $\text{CaCO}_3 \cdot \text{MgCO}_3$ ). Neither lime nor limestone react well with  $\text{SO}_2$  at ambient temperatures. At high temperatures ( $1500^\circ\text{F}$  -  $1800^\circ\text{F}$ ), both  $\text{CaCO}_3$  and  $\text{CaO}$  appear to react with  $\text{SO}_2$ . At these temperatures,  $\text{CaCO}_3$  is readily calcinated to  $\text{CaO}$ . The reaction of  $\text{SO}_2$  actually takes place with  $\text{CaO}$  even when  $\text{CaCO}_3$  is the material injected. This is a kinetic rather than a thermodynamic restriction (Ref 5-7).

The "throwaway" processes for removing sulfur oxides from gas streams involve the introduction of some sacrificial material. Such materials combine with the sulfur oxides to convert them into a removable liquid or solid. Either chemical reaction (absorption) or physical attraction (adsorption) may take place. Since the product will be discarded, the added material must be inexpensive. For this reason, the emphasis in throwaway process development has been placed on naturally occurring materials, such as limestone and dolomite.

#### APPROACH

This investigation evolved from prior work with coal gasification, fluidized bed combustion, and coal mixture fuels, and from a background understanding that direct lime or limestone injection does not remove  $\text{SO}_2$  effectively. The first step was to determine if lime would remove hydrogen sulfide formed during starved air combustion. This concept was evaluated using an equilibrium combustion computer program developed over many years at the NASA-Lewis Research Center. A description of this program is contained in Reference 8.

This program can solve the following problems:

- Equilibrium composition at a given temperature and pressure (Type TP).
- Adiabatic flame temperature and composition at a given temperature and pressure (Type HP).
- Detonation wave velocity and thermodynamic properties behind the wave for a given unburned gas temperature and pressure (Type DETN).
- Equilibrium and frozen expansion in a rocket nozzle for specified chamber pressure (Type RKT).

Program output not only includes the equilibrium mole fractions, but also the following properties of the mixture: Specific volume, molecular weight, enthalpy, and entropy. The method of solution is

based on minimization of the Gibbs function. Lagrangian multipliers are used, and a set of nonlinear algebraic equations is developed and solved by a Newton-Raphson iteration procedure.

Two problem types, HP and TP, were used to examine a generalized hydrocarbon fuel containing sulfur. A lime sorbent was added to the fuel for test cases. It was noted that the  $H_2S$  formation was dependent not only on oxygen concentration but also on temperature. That is, for a given equivalence ratio,  $H_2S$  was produced at low temperatures and replaced by  $SO_2$  at higher temperatures. Typical results are shown in Table 1.

Although the results of the computer study were affirmative, reaction time remained an unknown. Equilibrium calculations determine what reactions are possible thermodynamically. They do not determine how fast the reaction will occur. That is, it is possible that the desired reaction between sulfur and sorbent might require so much time that no practical reactor (boiler or furnace, for example) could be devised to contain it. Since the equilibrium calculation indicated that the desired reaction was possible, it was concluded that the viability of the concept should be determined experimentally.

The objective of the experiment was to determine if lime injected into a fuel-rich flame would remove hydrogen sulfide. Practical problems associated with the development and design of an actual burner were not considered here. It is stressed that neither design nor development was taken lightly, but the immediate issue was to isolate and resolve the chemistry and combustion problems.

#### DESIGN OF EXPERIMENT

A flame tube experiment was designed with the test setup as shown in Figures 1 through 4. The flame tube was an open pipe with a burner nozzle inserted in one end. A 20-foot-long, 6-inch schedule 40 pipe (6.065 inch I.D.), resting horizontally on three jack stands, was divided into four sections for ease of handling. Each section contained three ports for injecting reactants or withdrawing samples. The ports were numbered 1 through 12 starting at the burner end of the flame tube as shown in Figure 3.

It was determined from References 3 and 9 that a 1-second residence time would be appropriate since the combustion time for a 200-mesh (70-micron) particle varied from 0.06 to 1.5 seconds. The use of smaller particle sizes, 325 mesh (44 micron) or below, was anticipated for both coal and lime. Flame tube length and cross-sectional area were determined by the air flow from the burner and the nominal 1-second residence time. That is, a flow with a velocity of 900 ft/min would require 1.33 seconds to travel 20 feet. Flame tube size was influenced by scaling. A physically small experiment should be avoided if possible, because combustion experiments are very difficult to scale. Cold wall reactions influence results as reactor surface-area-to-volume ratios increase. This setup was considered a small, full-scale experiment.

One end of the flame tube was open, and a burner was inserted into the other end. An ordinary light oil burner with an air atomization nozzle (Sonicore 125H) and continuous electric spark ignition was used.

The Sonicore nozzle uses an expanding compressed air jet to impinge on a cup to form a resonance chamber. The acoustic wave and flow field thus generated effectively atomize the fuel coming around the air jet. During tests, the fuel flow was controlled by a needle valve downstream to a ball-in-tube rotameter. Utility compressed air, controlled by a gage and throttling valve, was used as the atomization air.

Kerosene was selected as the primary fuel for the tests. There was little to be gained by burning coal since the problem was to determine if lime would remove hydrogen sulfide in or near a flame zone. Kerosene was selected because it is inexpensive and easy to obtain, reasonably safe to work with, and its composition, although a mixture, is well defined.

Hydrogen sulfide gas was stored in liquid form in a pressure cylinder. The gas or vapor was metered through a float-in-tube rotameter in parallel with a mercury manometer. The hydrogen sulfide was injected into the flame tube through the second port. This was approximately the center of the flame zone. The flow rates used corresponded to 2-1/2% and 5% sulfur by weight of fuel.

Calcium oxide or lime was injected through the first port in the flame tube. The lime was a fine white powder with a particle size range from 1 micron to 10 microns. An air-operated sand blaster was used both to induce and to meter the flow of lime. The sand blaster was calibrated by correlating air pressure with lime mass flow rate. A calcium-to-sulfur mole ratio of 10 was used. This was high compared with the results published by others (Ref 10). Design optimization was considered secondary to determining whether or not the desired reactions would take place in a realistically short time.

Three flame variations were chosen based upon the following carbon monoxide volumetric concentration in the combustion gas: 10%, 5%, and 1%. All represented fuel-rich conditions. The 10% CO concentration was the most off stoichiometric. At the 10% CO concentration, the flame tube most closely approximated the first stage of the two-stage combustor. That is, a combustible mixture would be produced in the flame zone. This mixture would burn if air was added and if an ignition source was present. This condition is clearly visible in Figure 1 where a second flame is burning at the end of the flame tube.

As mentioned previously, two sulfur concentrations, based on 2-1/2% and 5% of the fuel weight, were used. The 2-1/2% concentration represents a medium sulfur coal, while the 5% concentration represents a high sulfur coal. Low sulfur levels were not considered because low sulfur coals do not require sulfur removal when burned in small boilers.\*

Two types of lime (CaO) were used. Since the limes were not obtained as a sorbent for sulfur compounds, neither the vendors nor the manufacturers will be identified. Type M was an industrial grade chemical purchased as "quick lime." Its exact composition was not known. Type B was a laboratory grade chemical referred to as purified quality. It was purchased as "anhydrous calcium oxide."

\*Federal Standards apply to boilers above 250 Mbtu/hr. However, local regulations may apply.

## TEST PROCEDURE

Because sample integrity is difficult to maintain and instrumentation is both complex and expensive in obtaining  $H_2S$  and  $SO_2$  data, it was decided to award a contract to an air pollution source testing laboratory to collect and analyze gas samples. (The award was made to BTC Laboratories, Ventura, CA). In addition to  $H_2S$  and  $SO_2$ ,  $O_2$ , CO and  $CO_2$  concentrations were to be obtained.

The hydrogen sulfide concentration was determined by cadmium sulfate impingement as per ASTM D-2385 "Hydrogen Sulfide and Mercaptan Sulfur in Natural Gas (Cadmium Sulfate-Iodometric Titration Method)." The sulfur dioxide was removed by impinging through a 3% hydrogen peroxide solution before the cadmium sulfate solution. The impinger train is shown in Figure 4. A 47-mm glass fiber filter was placed between the peroxide solution impingers and the cadmium sulfate to remove sulfur dioxide fumes. The sulfur dioxide was analyzed by E.P.A. Method 6. The  $SO_2$  is absorbed in a 3% peroxide solution and titrated with barium chloride to a Thorin indicator end point. The oxygen content was determined by a Taylor paramagnetic oxygen analyzer. The carbon dioxide and carbon monoxide values were obtained with the use of Horiba non-dispersive infrared analyzers.

Samples were often difficult to obtain. High temperatures, high particulate content, and soot plugged lines, probes, and filters. In addition, the excessive heat deteriorated the original sample probe. The probes were redesigned twice before a water-cooled version with an integral cyclone prefilter was fabricated. The remaining particulates were removed by a 4-inch glass fiber filter located upstream to the impingers. Most of these problems were overcome, but proper sampling remained difficult.

## TEST RESULTS

The computer program output was really only an input to the decision to proceed with experimental work. Based on the computer analysis shown in Table 1, it was anticipated that the experimental work would be successful. Sufficient data were obtained to verify the concept. While some questions were answered, others arose without being resolved. The difference in effectiveness between the Type B and Type M limes was not anticipated. The difficulty in obtaining samples was not anticipated by either the contractor or the author.

Reduced data are shown in Tables 2 through 8, and Figures 5 through 7. Table 2 shows lime sorbent effectiveness as the percentage reduction in total gaseous sulfur compounds measured as  $H_2S$  and  $SO_2$ . Percentage reduction calculations were made by comparing data at individual sample ports. For example, measurements taken at the burner end of the flame tube were not compared with data for the center or the downstream end. The reason for this precaution is that without lime injection, the sulfur concentration does not appear to remain constant along the flame tube. Since this is not possible physically, the sulfur is either locked in a compound that was not measured or the data were incorrect. The latter is more likely because the computer analysis showed only

trace amounts of compounds such as carbonyl sulfide (COS), for example. In any event, without lime injection, when the CO concentration is high, the sulfur concentration appears to increase along the flame tube. The opposite occurs when the CO concentration is low.

Tables 3 through 8 are included to assist with establishing data trends. For example, when the CO concentration was 10%, most of the sulfur existed as  $H_2S$ . When the CO concentration was 1%, most of the sulfur existed as  $SO_2$ . It should be noted that there was a striking decrease in sulfur removal or sorbent efficiency as  $H_2S$  was replaced by  $SO_2$ . Another interesting aspect was the short time required for  $H_2S$  conversion to  $SO_2$  when the CO concentration was low.  $H_2S$  was injected only 18 inches upstream to the first sampling port. Conversion to  $SO_2$  was complete at that point.

Although it was not possible to have complete confidence in any single datum point, the data present good collective information. As would be expected, the lime removes more sulfur as distance along the flame tube increases. The confidence in data also increases. The first sampling port was the most troublesome. If some of the low sulfur concentrations indicated at that point are valid, then an attempt should be made to freeze the reaction and remove or oxidize the spent sorbent.

The difference in behavior and effectiveness of the Type M and Type B lime sorbents was not expected. Type M was shown to be effective at the first sampling port when CO concentrations were low. These data, although repeated with consistency, are suspect. As can best be seen in Figures 5 through 7, Type B out performed Type M by a considerable margin. This was especially true at the downstream end of the flame tube when CO concentrations were high.

Outwardly, there appears to be little to choose between the two limes except for the difference in chemical grade. Both are fine, white powders and are supposed to have the same chemical composition. A simple wet chemical analysis did not determine a difference in the two. A scanning electron microscope indicated a slightly different surface condition as shown in Figures 8 and 9. This matter was discussed with the author of Reference 11. His experience showed that the temperature at which limestone is calcined is very important. If the temperature is high, the surface of individual lime particles tends to be less porous, has fewer irregularities with less surface area, and generally presents fewer potential reaction sites. Unfortunately, the difference in the photographs did not appear definitive, and the question has not been resolved.

## CONCLUSIONS AND RECOMMENDATIONS

The original objective was met since it was demonstrated that lime does react with hydrogen sulfide to capture sulfur compounds in low temperature, fuel-rich flames.

The two lime sorbents used should be analyzed further to determine why their effectiveness differed. This should include both overall performance as well as specific conditions where performance was inconsistent.

The effect of temperature on the absorption reaction should be evaluated. This could be accomplished by moving the lime injection point downstream to the flame zone.

The experimental oxidation of calcium sulfide to form gypsum should be examined by injecting air into the flame tube downstream to the lime reaction zone. Temperature effects must be considered since this experiment would simulate the second stage of a two-stage combustion process.

Although difficult to achieve in actual practice, attempts should be made to freeze reactions and to duplicate those conditions which provide desired experimental results.

#### ACKNOWLEDGMENT

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Table 1. Equilibrium Analysis of Sulfur Compounds  
in a Fuel-Rich Hydrocarbon Flame

Temperature (°K)	Mole Fractions				
	Without CaO		With CaO		
	H <sub>2</sub> S	SO <sub>2</sub>	H <sub>2</sub> S	SO <sub>2</sub>	CaS
800	0.00237	*	0.00001	*	0.00239
1,000	0.00233	*	0.00005	*	0.00233
1,200	0.00229	*	0.00020	*	0.00217
1,400	0.00205	0.00008	0.00052	0.00002	0.00180
1,600	0.00111	0.00076	0.00105	0.00068	0.00019
1,800	0.00029	0.00176	0.00030	0.00173	*
2,000	0.00005	0.00205	0.00006	0.00204	*
2,200	0.00001	0.00207	0.00001	0.00206	*
2,400	*	0.00203	*	0.00202	*

\*Less than 0.00001

Table 2. Summary of Laboratory Test Results

Output CO (%)	Input S (%)	Lime Type	Port 3		Port 7		Port 12	
			Total Sulfur (gr/ft <sup>3</sup> )*	Sulfur Reduct. (%)	Total Sulfur (gr/ft <sup>3</sup> )	Sulfur Reduct. (%)	Total Sulfur (gr/ft <sup>3</sup> )	Sulfur Reduct. (%)
10	5	None	4.17	0	4.96	0	5.4	0
10	5	B	2.51	39.8	2.43	50.9	1.0	81.6
10	5	M	1.85	55.6	2.99	39.7	3.02	55.9
10	2-1/2	None	2.28	0	2.27	0	2.72	0
10	2-1/2	B	1.89	17.1	1.1	51.3	0.9	66.9
10	2-1/2	M					1.81	33.5
5	5	None	1.2	0	1.17	0	0.89	0
5	5	B	0.36	70	0.77	34.2	0.18	79.8
5	5	M	0.46	61.7	0.36	69.2	0.48	46.1
5	2-1/2	None	0.6	0	0.55	0	0.64	0
5	2-1/2	B	0.1	83.3	0.40	27.3	0.04	93.8
5	2-1/2	M	0.22	63.3			0.39	39.1
1	5	None	2.02	0	1.34	0	1.20	0
1	5	B			1.02	23.9	1.18	0
1	5	M	0.40	80.2				
1	2-1/2	None	0.97	0	0.74	0	0.56	0
1	2-1/2	B			0.36	51.4	0.47	16.1
1	2-1/2	M	0.17	82.5				

\*grains per cubic foot.

Table 3. Laboratory Test Results for 10% Carbon Monoxide and 5% Sulfur Conditions

Lime Type	Port 3			Port 7			Port 12		
	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )
None	6,965	93	4.17	7,429	67	4.43	8,633	29	5.11
None				9,210	72	5.48	9,590	25	5.68
M	2,785	353	1.85	4,940	132	2.99	3,600	138	2.21
M							6,430	64	3.83
B	2,775	1,681	2.63	4,262	18	2.53	1,062		0.63
B	3,920	133	2.39	3,900	243	2.45	2,190	112	1.36
B				3,820	103	2.32			

Table 4. Laboratory Test Results for 10% Carbon Monoxide and 2-1/2% Sulfur Conditions

Lime Type	Port 3			Port 7			Port 12		
	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )
None	3,414	72	2.06	3,780	72	2.27	4,300	175	2.64
None	4,170	69	2.5				4,620	130	2.8
M							3,570	58	2.14
M							2,430	83	1.48
B	1,276	1,164	1.44	2,601	279	1.7	971	350	0.78
B	3,790	189	2.35	789	76	0.51	1,680	55	1.02

Table 5. Laboratory Test Results for 5% Carbon Monoxide and 5% Sulfur Conditions

Lime Type	Port 3			Port 7			Port 12		
	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )
None	787	1,241	1.2	877	781	0.98	1,037	935	1.16
None				583	1,700	1.35	541	517	0.62
M	230	548	0.46	516	99	0.36	660	168	0.49
M							787	13	0.47
B	647	86	0.43	522	786	0.77	208	89	0.18
B	248	249	0.29						

Table 6. Laboratory Test Results for 5% Carbon Monoxide and 2-1/2% Sulfur Conditions

Lime Type	Port 3			Port 7			Port 12		
	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )
None	556	460	0.6	477	474	0.56	298	516	0.48
None				346	577	0.54	314	1,040	0.8
M	17	137	0.1				264	550	0.48
M	500	70	0.34				15	474	0.29
B	77	98	0.1	57	508	0.33	42	33	0.04
B				53	763	0.48			

Table 7. Laboratory Test Results for 1% Carbon Monoxide and 5% Sulfur Conditions

Lime Type	Port 3			Port 7			Port 12		
	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )
None	12	3,417	2.02	77	2,190	1.34	74	1,952	1.20
B				180	1,852	1.20		2,006	1.18
B				28	1,389	0.84			
M	10	671	0.40						

Table 8. Laboratory Test Results for 1% Carbon Monoxide and 2-1/2% Sulfur Conditions

Lime Type	Port 3			Port 7			Port 12		
	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )	H <sub>2</sub> S (ppm)	SO <sub>2</sub> (ppm)	Total Sulfur (gr/ft <sup>3</sup> )
None	16	1,632	0.97	136	1,110	0.74	97	845	0.56
B				2	601	0.36	3	792	0.47
M	20	260	0.17						

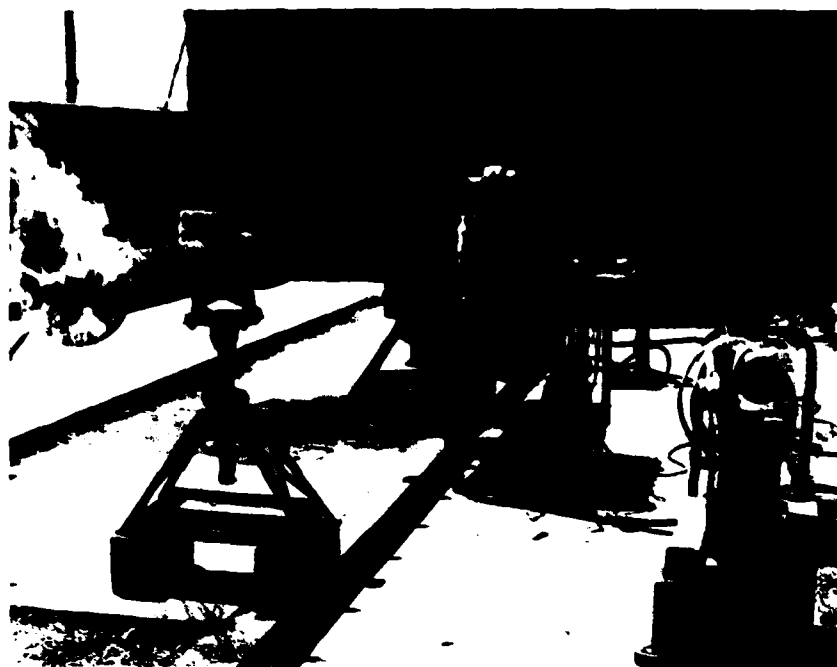


Figure 1. Upstream view of the flame tube. Note second ignition at the open end.



Figure 2. Downstream view of the flame tube.

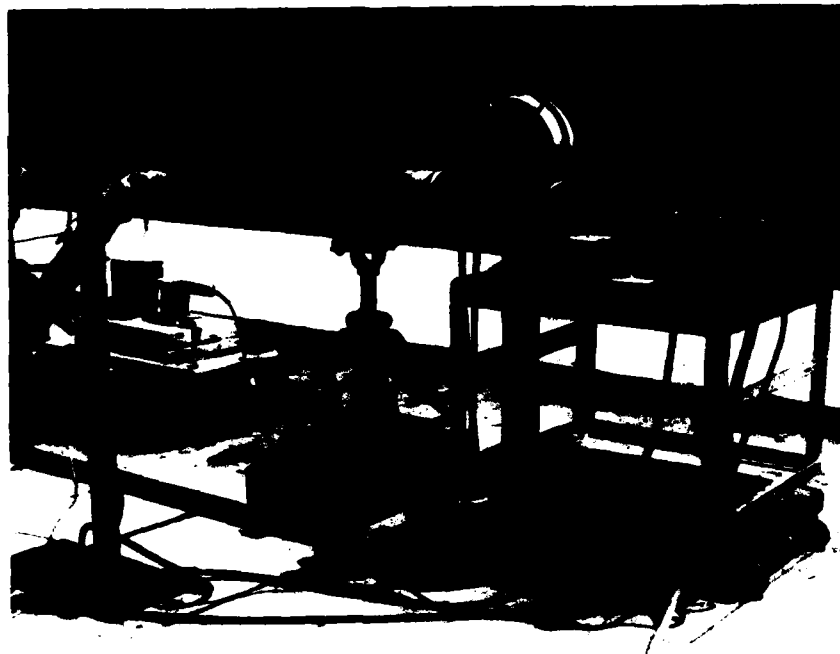


Figure 3. Burner inserted with lime injected in port number 1.



Figure 4. Sample train for data collection.

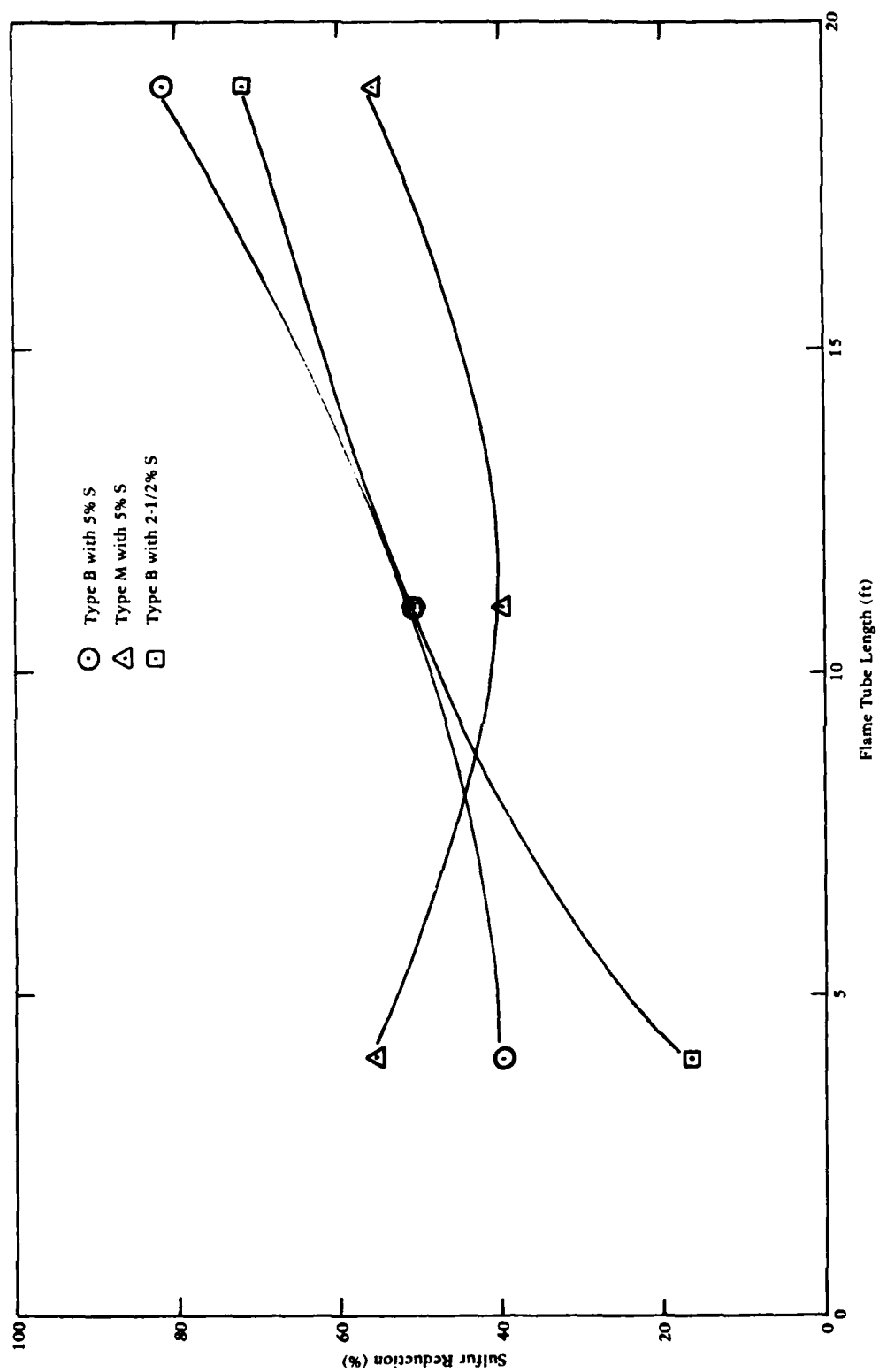


Figure 5. Sorbent performance for 10% carbon monoxide condition.



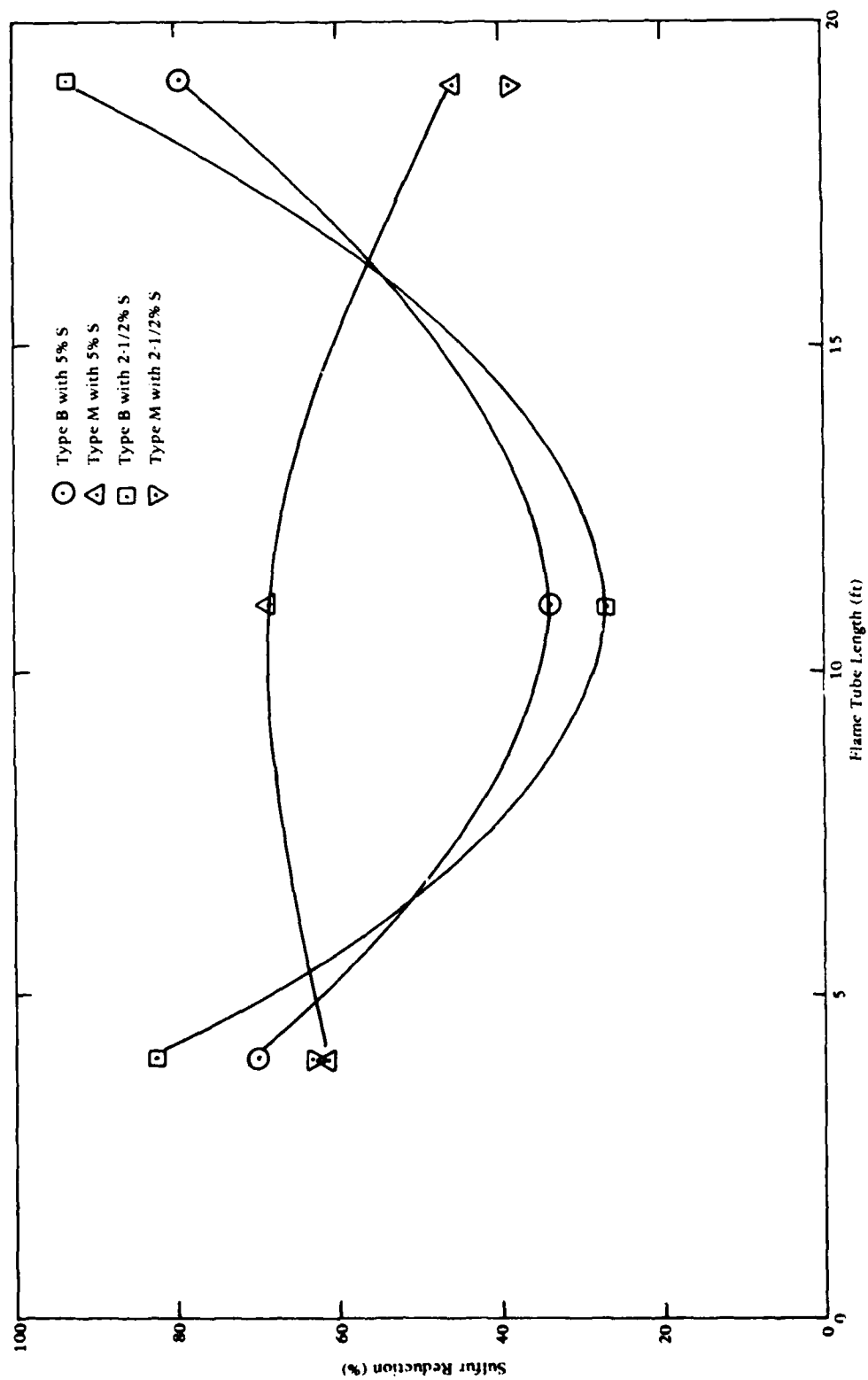


Figure 6. Sorbent performance for 5% carbon monoxide condition.

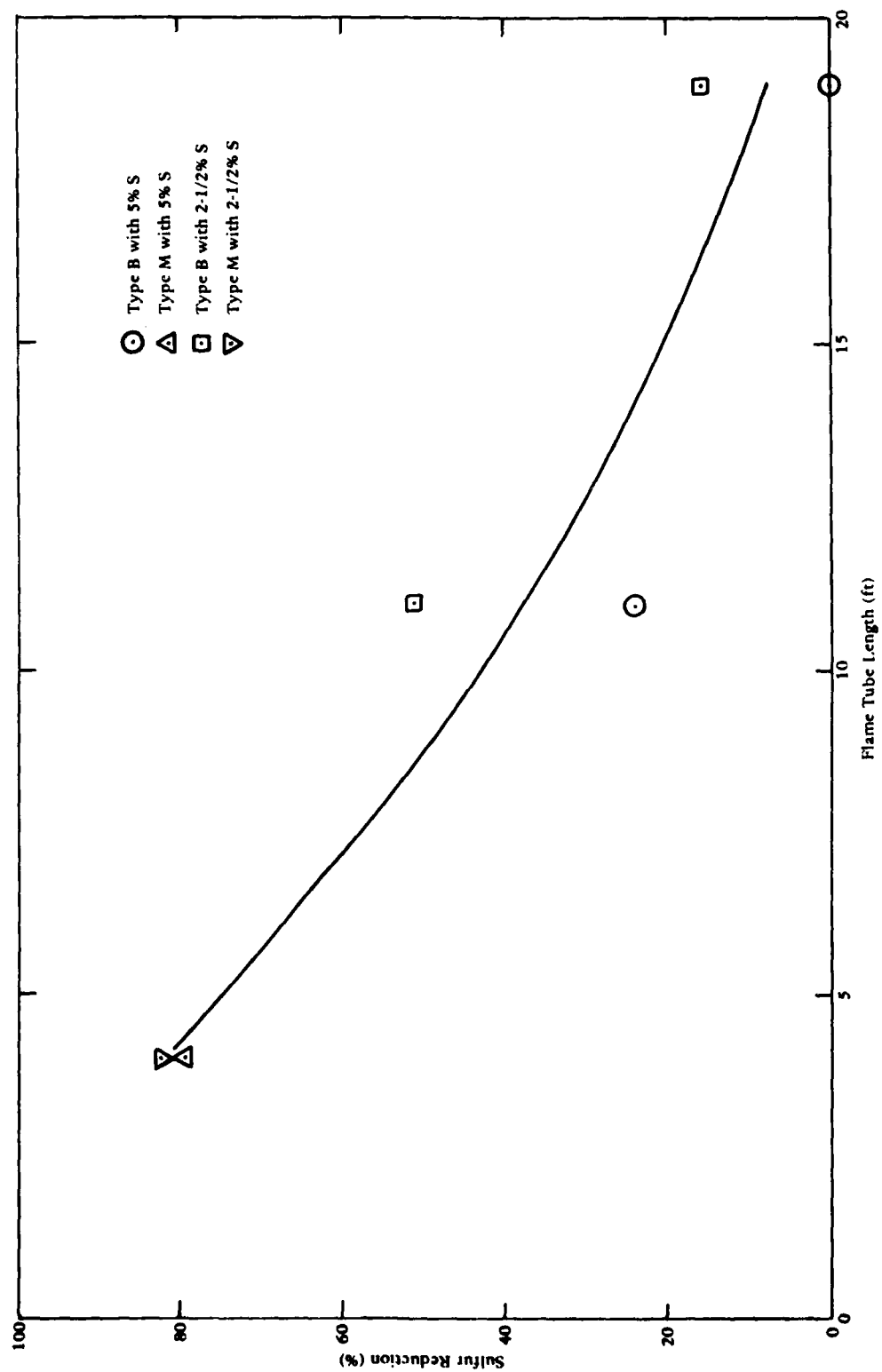
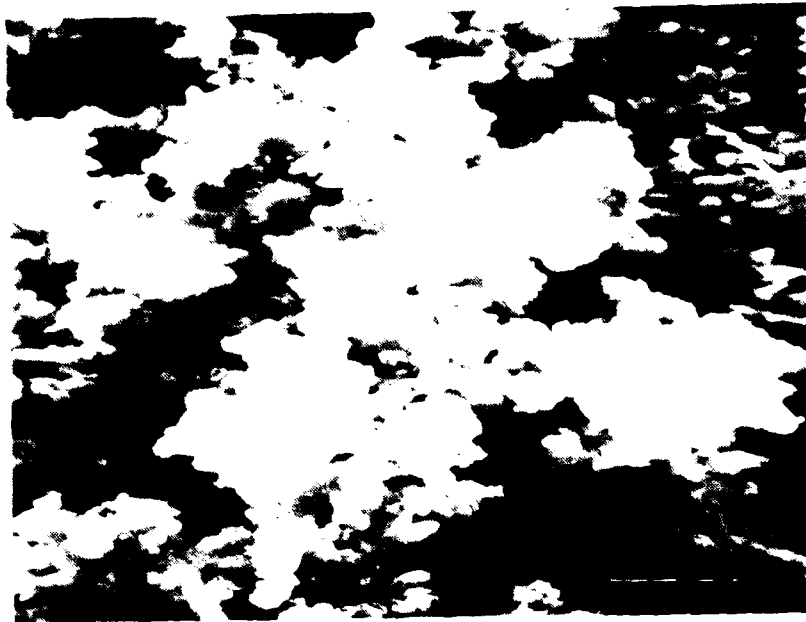


Figure 7. Sorbent performance for 1% carbon monoxide condition.

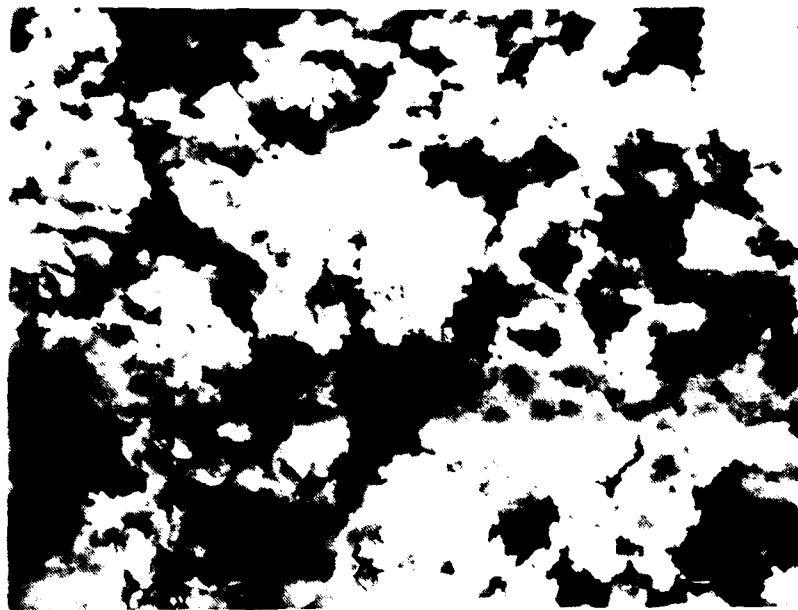


(a) 1000 magnification.

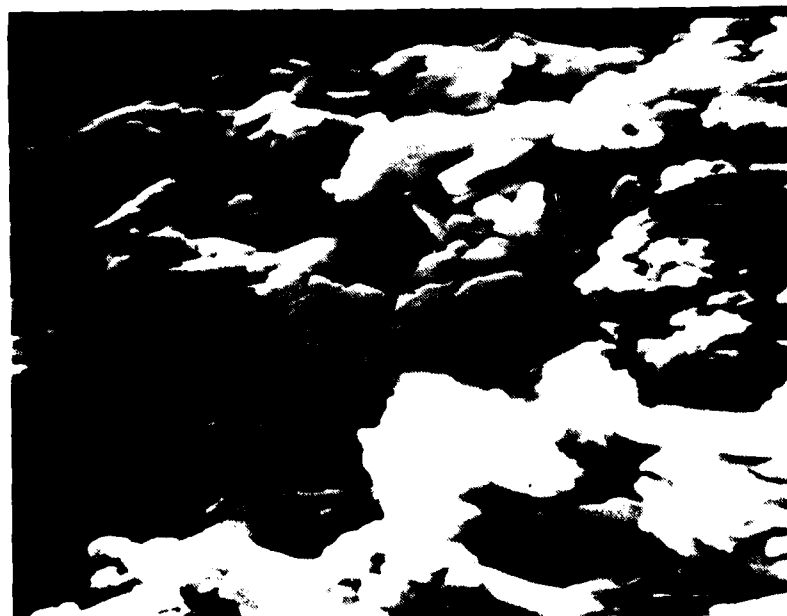


(b) 3200 magnification.

Figure 8. Type B lime magnified.



(a) 1000 magnification.



(b) 3200 magnification.

Figure 9. Type M lime magnified.

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